

MEASURING THICKNESS AND CONDUCTIVITY OF METALLIC LAYERS WITH EDDY CURRENTS

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INTRODUCTION

Coated metals are used increasingly for a variety of technological purposes; the coatings provide wear resistance, good electrical contact, corrosion protection, and thermal isolation. Consequently the ability to determine the thickness, conductivity, and structural integrity of such coatings is important for both process control and in-service inspection of parts. Presently ultrasonic, thermal, and eddy current inspection methods are used, depending on the circumstances. Current inspection practices using these methods are often limited in their ability to provide quantitative estimates of the important parameters. In this paper we present a robust method that uses eddy current measurements to determine the thickness and conductivity of uniform conductive layers.

The determination of the thickness and conductivity of metallic layers provides an interesting example of the inverse problem for a diffusion equation. Our analysis starts from the exact solution of the forward problem by Dodd and Deeds [1] for an air-core coil over a layered half-space. This solution is compared to the data using a least-squares norm and the conductivity and thickness are extracted by minimizing the norm. Our focus is primarily experimental, and the practical feasibility of the inversion method is shown.

Previously Kahn and Norton [2] have considered a similar problem involving concentric cylinders with an encircling coil. They also used a least-squares norm and obtained good results for their chosen applications. Nair and Rose [3,4] have studied the layered half-space problem in some detail theoretically, and have presented an exact method for a continuously varying one-dimensional profile. However, experimental data are not yet available that would allow a test of their proposed inversion method. Other recent work can be found in the technical reports of C.V. Dodd [5] and in references [6] and [7]. A more complete description of the work presented here can be found in [8].

FORWARD PROBLEM AND INVERSION METHOD

The geometry of the problems considered in this paper are illustrated schematically in Fig. 1. An air-core circular coil of rectangular cross-section is placed over a layered half-space with the coil axis perpendicular to the surface and its impedance is measured as a function of frequency. The conductivity of the layer is denoted by σ_1 and that of the substrate by σ_2 . Only nonmagnetic materials are considered, hence we use the permeability of free space μ_0 .

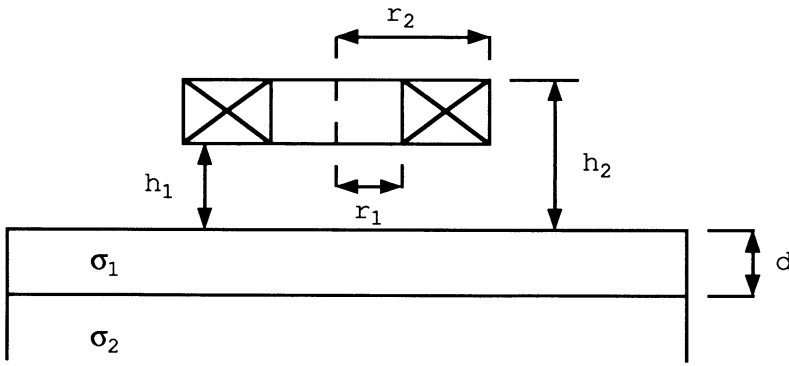


Fig. 1 Geometry and dimensions of the sample and probe.

The forward problem is to determine the impedance of the coil, given the frequency, the layer size, and the permeability and conductivity of the materials. This problem was solved by Dodd and Deeds [1]. The experimentally measured quantity is the difference in impedance for two measurements

$$\Delta Z = Z_L - Z_{HSP} \quad (1)$$

Here, Z_L denotes the impedance of the coil over a layer of a metal on a thick plate of the substrate which is approximated as a semi-infinite half-space. The impedance of the substrate is used as a reference, and is denoted by Z_{HSP} . The use of ΔZ facilitates the comparison of theory with experiment. For example, the electrical resistance of the wires that comprise the coil is not calculated in the formalism of Dodd and Deeds. However, this term cancels when the difference between Z_L and Z_{HSP} is taken. The impedance difference can be calculated from Dodd and Deeds formula as

$$\Delta Z = \frac{\pi \mu_0 n^2}{(h_2 - h_1)^2 (r_2 - r_1)^2} j \omega \int_0^\infty \frac{I^2(\alpha, r_1, r_2)}{\alpha^6} A(\alpha) \left[\frac{\alpha - \alpha_2}{\alpha + \alpha_2} + \phi(\alpha) \right] d\alpha, \quad (2)$$

where

$$I(\alpha, r_1, r_2) = \int_{\alpha r_1}^{\alpha r_2} x J_1(x) dx \quad (3)$$

$$A(\alpha) = e^{-2\alpha h_2} + e^{-2\alpha h_1} - e^{-\alpha(h_1 + h_2)} \quad (4)$$

$$\phi(\alpha) = \frac{(\alpha + \alpha_1)(\alpha_1 - \alpha_2) + (\alpha - \alpha_1)(\alpha_1 + \alpha_2)e^{2d\alpha_1}}{(\alpha - \alpha_1)(\alpha_1 - \alpha_2) + (\alpha + \alpha_1)(\alpha_1 + \alpha_2)e^{2d\alpha_1}} \quad (5)$$

$$\alpha_{1,2} = \sqrt{\alpha^2 + j\omega\mu_0\sigma_{1,2}}. \quad (6)$$

Figure 2 shows a comparison of theory and measurements made with an air core probe for the real part of the impedance. The curves shown in Fig. 2 have two distinctive features: a minimum and a zero crossing. The occurrence of the zero in the resistive component has a simple physical interpretation: namely, the power dissipation is the same in the layered sample and in the reference half-space of the substrate at that frequency.

The frequency of the minimum and the zero in ΔR depend strongly on the layer thickness as well as the electromagnetic properties of the layer and the substrate. Asymptotic analysis of the impedance difference formula for very thin layers and for small conductivity differences between layer and host supports this assertion. Consequently, we expect that an inversion method based on the frequency dependence of the impedance difference will be able to determine the layer thickness and electromagnetic properties.

The inversion method that we used is probably the simplest one possible. Namely, we used Eq.(2) to compute ΔZ for a variety of possible layer thickness and conductivities. We then found that set of parameters for which the theory curve was as close as possible to the experimental data. The least squares norm was our measure of closeness. Explicitly, we defined a cost function

$$Q = \sum_{i=1}^N [\Delta R_{theory} - \Delta R_{exp}]^2 \quad (7)$$

Here, the sum is over a set of N frequencies (typically N = 20). Q was minimized by using a simplex direct-search procedure.

The residual, Q, depends only on the resistive component of the impedance measurement. We found that the uncertainties due to the coil geometry (the precise coil winding geometry) seemed to be more serious in the reactive (inductive) components of the impedance. Consequently, we focused our inversion efforts on ΔR , which seemed to be less sensitive to these model errors.

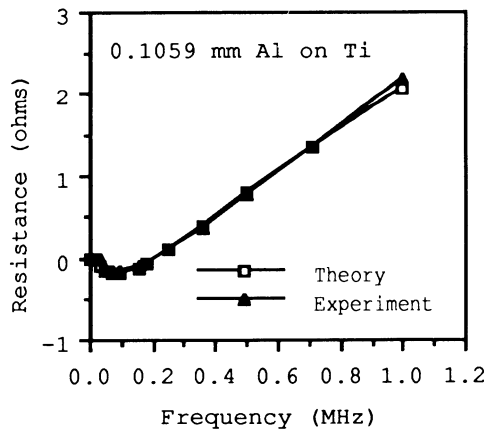


Fig. 2. Comparison of theory and measurements for the real part of the impedance change.

EXPERIMENT

We confined our measurements to 401 points lying between 1 kHz and 1 MHz. Measurements of the coil impedance were obtained both on the layered material and on a part of the substrate not covered by the layer. The difference of the two impedances, ΔZ , was recorded at each frequency.

Measurements were taken for a variety of samples, including layers of aluminum and copper over 7075 aluminum, 304 stainless steel, copper, and Ti-6Al-4V. Seven foil samples of pure (99.999) aluminum were prepared by rolling to different thicknesses ranging from 20 to 500 μm . Copper foils ranging from 100 to 500 μm were prepared in a similar fashion using copper 101. For most of the measurements we report here these foils were placed in contact with a given substrate and the probe then placed upon the foil under a small spring load. We found that the measurements of ΔZ were sensitive to small variations in liftoff between measurements on and off the layer and the use of spring loading on the probe helped to achieve reproducible results. Since the eddy currents flow parallel to the surface, we expected no effects owing to the lack of bonding between the two materials. We checked this assumption by preparing one set of five specimens of copper foils diffusion bonded to 304 stainless steel. The foils used were the same nominal thickness as the unbonded foils mentioned above. Measurements of ΔZ for bonded and unbonded specimens revealed no significant difference.

The coils that we used for most of the measurements are a specially constructed pair of nominally identical air-core coils. Although the electrical properties are very closely matched, the fields produced by these two coils differ enough to produce roughly 40% differences in ΔZ for small surface cracks [9]. Of the two coils, designated L and M, both we and others [10] have found the best agreement between experiment and theory (Eq. (2)) for coil L; unless otherwise noted, the results we present below are for this coil.

Because we found some disparity between theory and experiment for these two air-core probes, which we attribute to the lack of precision in winding, we also made measurements with two larger air-core coils which were precision wound. We used these coils to make measurements on 431 and 553 μm thick copper layers on 304 stainless steel and we obtained better agreement between theory and experiment than with either probe L or M.

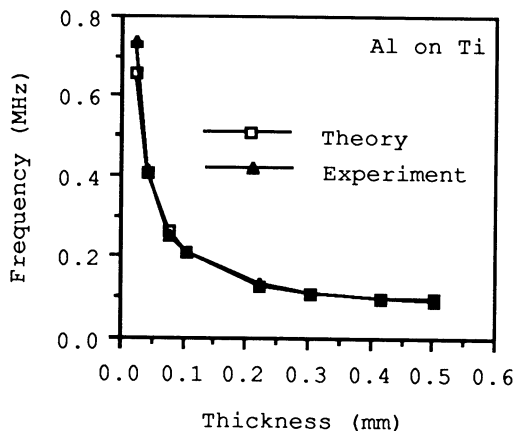


Fig. 3. Frequency at which the real part of the impedance change goes through zero.

Figure 3 shows experimental measurements of the zero-crossing frequency for the seven aluminum foils specimens on Ti-6Al-4V compared to theoretical predictions. We note that the curve changes most rapidly for small thicknesses and varies slowly for the thickest specimens. The zero-crossing of ΔR can serve as a sensitive measure of layer thickness if the layer is uniform and its conductivity is known. Indeed, any coil would be suitable for this type of measurement as long as the curve of zero-crossing frequency vs. thickness were calibrated on specimens of known conductivity and thickness.

RESULTS AND DISCUSSION

Important experimental variables include: (1) the precision of the coil construction, (2) the ratio of the conductivity of the layer and the substrate, (3) the ratio of the layer thickness to the coil radius, and (4) the range of frequencies for which the impedance change could be accurately determined. Probe L was used for most of the data taking since its radius was relatively close to the thickness of the layers being measured and it thus provided a greater ability to simultaneously determine both the conductivity and thickness.

Figures 4 and 5 show estimates for the thickness and conductivity of a layer of copper on stainless steel (one of our best results). Each measurement was repeated five times. We report the range of estimates that result from inverting these five measurements and also the average data.

The thickness and conductivity were determined relatively well for thicknesses ranging from 100 to 500 μm . The estimates became increasingly unreliable for smaller thicknesses. The increasing loss of reliability can be explained by asymptotic analysis, which shows that only the product of the thickness and the conductivity change can be determined if the layer's thickness is much less than the coil's radius. Consequently, if the conductivity of the layer is known, we can find the thickness, and if the thickness is known the conductivity can be determined. When we inserted the nominal value of thickness or conductivity of aluminum in Eqn. (7), estimates for the other variable were improved generally and were dramatically improved for small layer thicknesses.

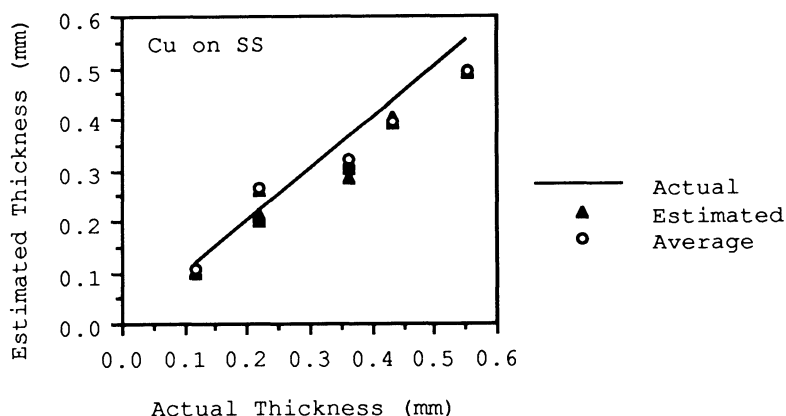


Fig. 4. Estimated thickness versus actual thickness; both thickness and conductivity were estimated simultaneously. The triangles show the estimates for each measurement. The circles show the result of inverting the average of the measurements.

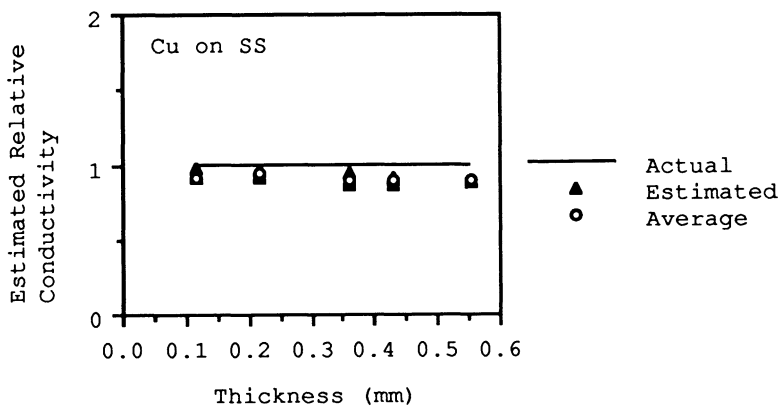


Fig. 5. Estimated relative conductivity as a function of layer thickness; both thickness and conductivity were estimated simultaneously.

The large number of samples analyzed precluded making a large number of independent measurements for each combination. However, for one case (a layer of copper on stainless steel) nineteen measurements were made. These data were inverted for the thickness and the conductivity by varying these parameters simultaneously. For this representative case, the thickness is estimated to be $115 \pm 10 \mu\text{m}$, whilst the conductivity is estimated to be $(5.34 \pm 0.54) 10^7 \text{ S/m}$. This compares to actual values of $115 \pm 2 \mu\text{m}$ and $5.80 10^7 \text{ S/m}$.

We found that the inversion was adequate if data at frequencies up to twice the zero-crossing frequency were included. These effects were seen most clearly in estimating the properties of unsupported layers of aluminum in free-space (there is no zero over the measured frequency range).

There are many layered materials that cannot be adequately represented by such a simple model. For example, case hardened or decarburized layers at the surface of metals are expected to have a conductivity profile that changes continuously with depth. Research is currently under way to develop methods of determining the properties of surface layers with diffuse boundaries.

In summary, the conductivity and thickness of layers on conducting materials can be determined from quantitative frequency-dependent eddy-current measurements for a wide variety of problems of practical interest.

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